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Hydrothermal carbonization of sugarcane bagasse via wet torrefaction in association with microwave heating

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HIGHLIGHTS

- ▶ Hydrothermal carbonization of sugarcane bagasse is studied using wet torrefaction.
- ▶ The biomass is torrefied in water or dilute sulfuric acid solution.
- ▶ Microwaves are employed to heat the solutions and the temperature is fixed at 180 °C.
- ▶ The higher heating value of bagasse can be increased up to 20.3%.
- ▶ The calorific value of torrefied biomass can be predicted well by correlations.

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ABSTRACT

Hydrothermal carbonization of sugarcane bagasse using wet torrefaction is studied. The biomass is torrefied in water or dilute sulfuric acid solution and microwaves are employed to heat the solutions where the reaction temperature is fixed at 180 °C. The effects of acid concentration, heating time and solid-to-liquid ratio on the performance of wet torrefaction are investigated. It is found that the addition of sulfuric acid and increasing heating time are conducive to carbonizing bagasse. The calorific value of bagasse can be increased up to 20.3% from wet torrefaction. With the same improvement in calorific value, the temperature of wet torrefaction is lower than that of dry torrefaction around 100 °C, revealing that wet torrefaction is a promising method to upgrade biomass as fuel. The calorific value of torrefied biomass can be predicted well based on proximate, elemental or fiber analysis, and the last one gives the best estimation.

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1. Introduction

Biomass is an important and abundant resource on the earth because it can be generated through photosynthesis worldwide. Biomass also plays a substantial role as the energy supplier in that it has been widely consumed for the purpose of getting heat and power. Lignocellulosic biomass wastes are featured by their non-edible characteristic; hence they have no risk causing food shortage when the wastes are consumed for energy. For this reason, the utilization of lignocellulosic biomass wastes as fuels has attracted remarkable interest in the development of bioenergy. Lignocellulosic biomass wastes may come from forest industry, energy crops, agricultural residues and grass (Yan et al., 2009). However, some challenges are encountered when these wastes are pretreated, stemming from their diverse nature. Their hygroscopic feature and low energy density also make the storage and transport inefficient and expensive. To resolve the aforementioned problems, torrefaction, a biomass pretreating process, is a promising method to homogenize lignocellulosic biomass wastes and produce hydrophobic, stable and energy-dense solid fuels. For example, in the study of Felfi et al. (2005), it was mentioned that the lower moisture contained in torrefied biomass could be the result of tar condensation inside the pores. This obstructed the passage of moist air through the solid, thereby avoiding the condensation of water vapor. Another reason for this could be the apolar character of condensed tar on the solid; this also prevented the condensation of water vapor inside the pores. The lignocellulosic structure of biomass is damaged from torrefaction, especially on hemicellulose, so that the grindability of biomass is improved greatly. On account of these advantages, it is more suitable for torrefied biomass to be co-fired or co-gasified with coal (Strege et al., 2011).

Torrefaction can be classified into a dry process and a wet one. Dry torrefaction is typically performed in the temperature range of 200–300 °C with the reaction time between 30 min and several

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hours (Sadaka and Negi, 2009; van der Stelt et al., 2011) where nitrogen is commonly employed as a carrier gas. Wet torrefaction, which is also spoken of as hydrothermal carbonization, is carried out at temperatures of 180–260 °C where biomass is immersed in solutions with gauge pressure up to 4.6 MPa (Lynam et al., 2011). The reaction time of wet torrefaction is usually in the range of 5–240 min. In reviewing recent literature, a number of studies concerning dry torrefaction have been reported (Chen and Kuo, 2010; Rousset et al., 2011; Li et al., 2012). On the other hand, relatively little research has been performed on wet torrefaction. Yan et al. (2009) pretreated loblolly pine by both dry torrefaction (nitrogen at 250–300 °C) and wet torrefaction (hot compressed water at 200–260 °C). They pointed out that wet torrefaction was more successful than dry torrefaction in energy densification under similar mass yield. Yan et al. (2010) also carried out the pretreatment of loblolly pine with hot compressed water at temperatures of 200–260 °C for 5 min. They addressed that the reaction temperature had significant influence on reaction mechanism and production distribution, that is, increasing temperature increased fuel calorific value and decreased mass yield. Lynam et al. (2011) used acetic acid and/or lithium chloride solutions to pretreat loblolly pine at 230 °C for 5 min and found that the addition of acetic acid and/or lithium chloride increased energy density of solid product.

The aforementioned wet torrefaction was practiced through conductive and convective heating. If mediums pertain to dielectrics, microwave irradiation appears as an alternative method to achieve heating. Unlike conventional conduction and convection where heat is delivered through superficial heat transfer, microwave irradiation induces an interaction between heated object and applied electromagnetic field to create heat inside the material (Rodrigues et al., 2011; Chen et al., 2011). When microwaves are used to treat lignocellulosic biomass, it selectively heats the more polar part and creates a "hot spot" if the dielectric material is inhomogeneous. This results in an "explosion" effect among the particles and the properties of lignocelluloses are changed (Hu and Wen, 2008; Ma et al., 2009). Considering wet torrefaction using dilute sulfuric acid, water, sulfuric acid, cellulose and hemicellulose belong to dielectrics (Ooshima et al., 1984). Consequently, the dilute acid solution and biomass can be heated by microwaves through a process of dielectric heating (Jones et al., 2002). This implies, in turn, that microwaves are able to penetrate into the solution and the lignocellulosic material through radiation, thereby achieving rapid and volumetric heating. As a whole, the advantages of material heating by microwave irradiation include: (1) reducing heating or pretreating time; (2) providing rapid and volumetric heating; (3) possessing the ability of instantaneous start-up and stop of heating; and (4) diminishing reactor size (Gabriel et al., 1998; Jones et al., 2002; Hu and Wen, 2008).

It is evident that wet torrefaction in association with microwave irradiation is an effective and promising method to upgrade biomass for producing solid fuels. However, reviewing recent literature indicates that very few studies have been performed concerning wet torrefaction with microwave-assisted heating. To provide a comprehensive insight into the pretreating performance of wet torrefaction in a microwave irradiation environment, property variation of sugarcane bagasse will be investigated. Particular attention is paid to the effects of acid concentration, solid load and heating time on the pretreating results. Sugarcane bagasse upgraded from wet torrefaction and dry torrefaction will also be compared with each other.

2. Experimental

2.1. Raw material

Sugarcane bagasse acquired from Taiwan Sugar Corporation in Tainan, Taiwan, was selected as raw material to be studied. The bagasse was washed thoroughly with tap water until the washings were clean and colorless. Thereafter, the washed bagasse was dried in an oven at 105 °C for 24 h. The dried bagasse was preliminarily grinded and sieved to particle sizes less than 40 mesh (i.e. <0.42 mm). Then the prepared bagasse was stored in a desiccator at room temperature until torrefaction was carried out.

2.2. Wet torrefaction

In the experiments of wet torrefaction, 10 g of bagasse was mixed with deionized water or sulfuric acid solution at room temperature. Afterward, the mixture was transferred into a cylindrical reactor (50 mm i.d. × 318 mm length) which was a Teflon vessel. The reactor was placed in a microwave oven and the vessel allowed microwaves irradiating into the reactor for heating the mixture. When samples were pretreated, the microwave oven was operated at the frequency of 2.45 GHz. The maximum power of the microwave oven was 900 W and the current output from the power controller was fixed at 10 A. When wet torrefaction was implemented, the reactor was removed from the oven and cooled to room temperature. The torrefied bagasse was separated by filter paper (diameter = 110 mm) with the mesh size of 1 μm. The filtered cakes were washed by hot deionized water (500 mL and 85 °C) five times to eliminate the acid remained on the particles. This procedure could diminish the effect of acid on subsequent analyses of the materials. (Chen et al., 2010b). Subsequently, the filtered solid particles were dried at 105 °C for 24 h for further analysis.

2.3. Dry torrefaction

In each run of dry torrefaction, 6 g of bagasse was placed in a reaction tube and the tube was situated in a tube furnace. When samples were torrefied, the duration was fixed at 1 h. Nitrogen was continuously blown into the reaction tube to keep the samples in a non-oxidizing environment and to remove volatiles produced from the thermal degradation of bagasse. The flow rate of nitrogen was controlled at 100 mL min^{-1} (25 °C). The torrefied bagasse was also dried at 105 °C for 24 h for further analysis.

2.4. Material analysis and experimental quality

The raw and torrefied materials were analyzed through fiber, proximate, elemental (ultimate), calorific, thermogravimetric and particle size analyses. In the fiber analysis, hemicellulose, cellulose and lignin were measured following the method adopted in a previous study (Chen et al., 2010a). The proximate analysis was performed in accordance with the standard procedure of American Society for Testing and Materials (ASTM). The elemental analysis was carried out using an elemental analyzer (Elementar Vario EL III). The higher heating values of samples were measured by a bomb calorimeter (IKA C5000 Basic). The thermogravimetric and particle size analyses were carried out by a thermogravimetry (TG, PerkinElmer Diamond TG/DTA) and a laser diffraction analyzer (HORIBA LA 950V2), respectively. The maximum allowed weight of sample in the TG was around 5 mg; the initial weight of each sample in the experiment of TGA was thus controlled at 5 mg or so. Nitrogen with the volumetric flow rate of 100 mL min^{-1} was blown into the TG and the heating temperature in the TG ranged from 25 to 800 °C. In the study of Luangkiattikhun et al. (2008), the decomposition peaks of hemicellulose and cellulose in oil-palm solid waste could be clearly identified when the heating rate was no less than 20 °C min^{-1}. For this reason, the heating rate of 20 °C min^{-1} was adopted to investigate the thermal decomposition of raw and torrefied bagasses in TGA. When the temperature reached 105 °C, it was held for 10 min to completely remove moisture and serve a basis of analysis. Prior to performing experiments, both

Table 1
Experimental conditions of wet torrefaction.

Solids content (g)	Temperature (°C)	SLR[a] (g mL^{-1})	Heating time (min)	H_2SO_4[b] (mL)	Water (mL)	H_2SO_4 solution (M)
10	180	0.1	5	0	100	0
			15	0	100	0
			30	0	100	0
		0.1	5	10	90	0.1
			15	10	90	0.1
			30	10	90	0.1
		0.2	5	5	45	0.1
			15	5	45	0.1
			30	5	45	0.1

[a] SLR: solid-to-liquid ratio.
[b] The concentration of H_2SO_4 is 1 M.

the wet and dry torrefaction systems were leak tested using nitrogen to ensure the measurement quality. The experiment under any given condition was usually carried out more than twice. The results were fairly uniform between each run and the relative error was less than 7%.

2.5. Experimental conditions

In the current study, the temperature of wet torrefaction was fixed at 180 °C and the influences of solid-to-liquid ratio (0.1 and 0.2 g mL^{-1}), heating time (5, 15 and 30 min) and sulfuric acid concentration (0 and 0.1 M) on the performance of wet torrefaction were taken into account. Detailed operating conditions of wet torrefaction are tabulated in Table 1. In regard to dry torrefaction, five temperatures of 210, 230, 250, 270 and 290 °C covering light, mild and severe torrefactions (Chen and Kuo, 2011) served as the basis of test.

3. Results and discussion

3.1. Fiber analysis

When bagasse is pretreated via wet torrefaction, hemicelluloses contained in the material is decreased in a significant way (Table 2). For example, for bagasse torrefied in water with the heating time of 30 min, hemicellulose content decreases from 29.92 to 4.37 wt.%. If bagasse is torrefied by sulfuric acid solution, hemicellulose can be further consumed. When water is used as the torrefaction medium and the heating time increases from 5 to 30 min, hemicellulose content declines from 10.59 to 4.37 wt.%. This reflects that the heating time plays a crucial role in depleting hemicellulose. Once the sulfuric acid solution (0.1 M) is employed, a large amount of hemicellulose is removed even though the heating time is as short as 5 min. It follows that the addition of sulfuric acid into water substantially intensifies the decomposition of hemicellulose. When the solid-to-liquid ratio (SLR) is 0.2 g mL^{-1}, the weight percentage of hemicellulose in torrefied bagasse is less than that with SLR = 0.1 g mL^{-1}. This is due to relatively more cellulose and lignin being retained from wet torrefaction at SLR = 0.2 g mL^{-1}. By virtue of pronounced decrease in hemicellulose from wet torrefaction, the relative contents of cellulose and lignin rise.

3.2. Thermogravimetric analysis

When thermogravimetric analyses (TGA) and derivative thermogravimetric (DTG) analyses of raw and torrefied bagasses are examined, their thermal degradation mainly occurs at temperatures between 250 and 400 °C (Fig. 1), regardless of what values of acid solution concentration and SLR are. In the study of Yang et al. (2007), they outlined that the decomposition temperatures of hemicellulose, cellulose and lignin were in the ranges of 200–315, 315–400 and 160–900 °C, respectively, stemming from their inherent difference in lignocellulosic structure. Meanwhile, the study of Blasi (2008) suggested that the maximum thermal degradation rates of hemicellulose and cellulose in beech wood developed at around 290 and 350 °C, respectively, and their peaks were clearly identified. Based on the two studies, the peaks of hemicellulose and cellulose in raw bagasse can be clearly identified at 316 and 365 °C, respectively. In water torrefaction, the peak of hemicellulose disappears (Fig. 1a). This corresponds to the behavior of consuming a large amount of hemicellulose observed in Table 2. A comparison between wet torrefactions with water and acid solution, the peaks of cellulose shown in Fig. 1b and c are not as high as those in Fig. 1a, and increasing heating time decreases the amplitude of the peak. This reveals that the structure of cellulose is also destroyed to a certain extent by wet torrefaction.

3.3. Proximate analysis

When bagasse undergoes wet torrefaction, the moisture content in the samples decays from around 9 to 2–4 wt.% (Fig. 2a), elucidating the less hydrophobic feature in torrefied bagasse. This characteristic resembles the results of dry torrefaction (Acharjee et al., 2011; Li et al., 2012). Unlike dry torrefaction, it is of interest that the volatile matter (VM) in bagasse increases when wet torrefaction is performed (Fig. 2b), except at SLR = 0.1 g mL^{-1} along with 30 min heating. This arises from the fact that the hydrolysis of bagasse converts lignocelluloses into short chain hydrocarbons (Boussarsar et al., 2009) which are contained in VM. The VM in torrefied bagasse is thus increased compared to that in raw one. When the heating time and acid concentration increase or the SLR is lower (e.g. 0.1 g mL^{-1}), it leads to a decrease in VM. From the profiles of fixed carbon (FC), it can be seen that the addition of acid catalyst with longer heating time (i.e. 15 or 30 min)

Table 2
Fiber analyses of raw and torrefied bagasses.

Material	SLR[a] (g mL^{-1})	H_2SO_4 (M)	Heating time (min)	Hemicellulose (wt.%)	Cellulose (wt.%)	Lignin (wt.%)	Other (wt.%)
Raw bagasse				29.92	48.45	17.12	4.51
Torrefied bagasse	0.1	0	5	10.59	55.47	17.65	16.29
			15	5.07	58.35	22.02	14.56
			30	4.37	60.04	21.27	14.32
	0.1	0.1	5	4.60	53.41	31.15	10.83
			15	0.10	47.89	37.38	14.99
			30	0.62	41.67	43.03	15.94
	0.2	0.1	5	1.54	56.17	31.43	10.86
			15	0.72	53.53	34.46	11.29
			30	1.05	49.53	38.82	10.60

[a] SLR: solid-to-liquid ratio.

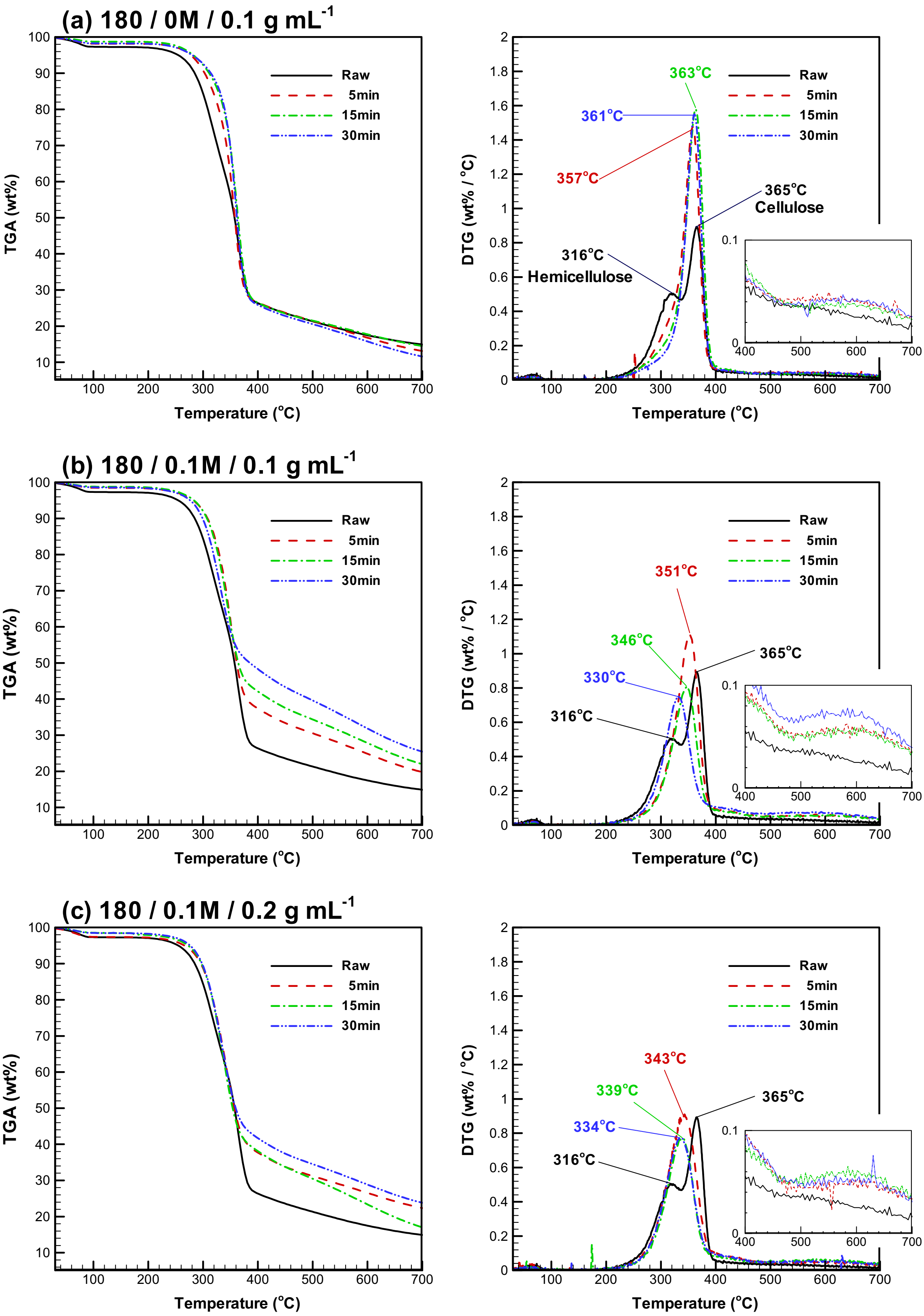

Fig. 1. Distributions of TGA and DTG at the operating conditions of (a) SLR = 0.1 g mL^{-1} with water torrefaction, (b) SLR = 0.1 g mL^{-1} with 0.1 M acid solution, and (c) SLR = 0.2 g mL^{-1} with 0.1 M acid solution.

facilitates hydrothermal carbonization of bagasse (Fig. 2c). The lower FC for bagasse pretreated in water is due to the higher VM contained in the torrefied material (Fig. 2b). It is worthy of note that the ash content in bagasse under water torrefaction is lower

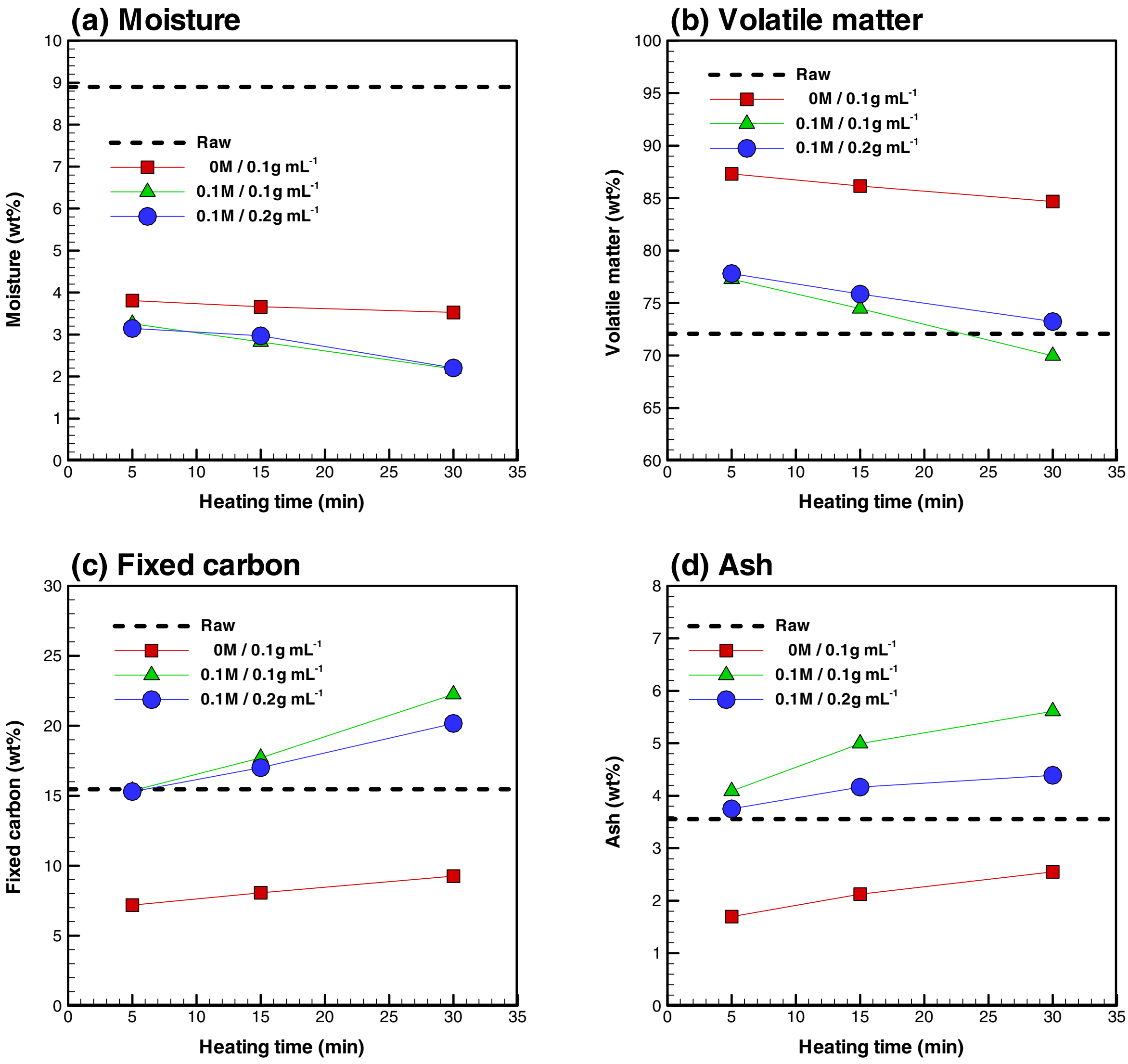

Fig. 2. Profiles of (a) moisture, (b) volatile matter, (c) fixed carbon and (d) ash with respect to heating time.

than that in raw bagasse. This is attributed to that partial ash in bagasse is washed by water in a high-temperature environment (Bridgwater, 2012). Wet torrefaction with acid solution can also remove ash; however, more solid is also consumed. This is the reason that the ash content for bagasse undergoing acid solution pretreatment is higher than that in raw bagasse. Overall, within the

Table 3
Elemental analyses of raw and torrefied bagasses.

Material	SLR[c] (g mL^{-1})	H_2SO_4 (M)	Heating time (min)	Ash (wt.%)	Elemental analyses (wt.%)				
					C	H	N	O	S
Raw bagasse				3.55	39.78	5.32	0.37	50.98	0
Torrefied bagasse	0.1	0	5	1.70	44.48	4.56	0.38	48.88	0
			15	2.13	45.52	4.77	0.35	47.23	0
			30	2.55	45.10	4.98	0.35	47.02	0
	0.1	0.1	5	4.09	50.56	5.43	0.26	39.66	0
			15	5.00	52.35	5.45	0.38	36.82	0
			30	5.61	51.95	4.34	0.34	37.76	0
	0.2	0.1	5	3.75	47.09	5.10	0.27	43.79	0
			15	4.17	51.33	4.96	0.28	39.26	0
			30	4.39	49.74	5.03	0.27	40.57	0
Peat[a]				4.2	48.03	5.51	0.82	41.11	0.21
Lignite[b]				10.62	63.63	4.08	0.96	19.53	1.18

[a] Hirai et al. (1990).
[b] Suuberg et al. (1978).
[c] SLR: solid-to-liquid ratio.

investigated ranges of acid concentration, SLR and heating time, the proximate analysis is more sensitive to acid concentration. Alternatively, the influences of SLR and heating time on the contents are relatively slight.

3.4. Elemental analysis

Hydrothermal carbonization of bagasse from wet torrefaction can be clearly observed from elemental analysis (Table 3). The carbon content in raw bagasse is 39.78 wt.% and it can be increased up to 52.35 wt.% at the conditions of SLR = 0.1 g mL^{-1} and 15 min heating time. This accounts for 32% increment in carbon content. The values of atomic H/C and O/C ratios in raw bagasse are 1.605 and 0.961, respectively, and they are in the ranges of 1.003–1.325 and 0.528–0.824, respectively, when bagasse is pretreated by wet torrefaction. This implies that the chemical formula of bagasse is transformed from $CH_{1.605}O_{0.961}$ to $CH_{1.003-1.325}O_{0.528-0.824}$. It is thus recognized that the atomic hydrogen and oxygen contained in bagasse are abated notably. The loss of H and O from wet torrefaction is due to the reactions of dehydrogenation, deoxygenation and dehydration processes. Upon inspection of the plot of atomic H/C ratio versus atomic O/C ratio in van Krevelen diagram (Fig. 3), the correlation coefficient (r) of the data is 0.755. This value is close to the strong correlation ($r \geqslant 0.8$). This reflects that the atomic H/C ratio and the atomic O/C ratio of the samples are almost characterized by a strong linear correlation. The atomic ratios of H/C and O/C of peat (Hirai et al., 1990) and lignite (Suuberg et al., 1978) are also plotted in Fig. 3 for comparison. Apparently, the atomic ratios of H/C and O/C of bagasse with water torrefaction are closer to that of peat. Alternatively, they have a trend to approach lignite when bagasse is torrefied by the sulfuric acid solution.

3.5. Heating value of bagasse

Solid and energy yields are two important indexes to evaluate the performance of torrefaction. The solid yield is defined as the mass ratio of dried torrefied bagasse to dried raw one, whereas the energy yield is defined as their energy ratio. Fig. 4 depicts that both the solid and energy yields go down with increasing heating time and the solid yield is always lower than the energy yield. From the profile of energy enhancement factor (EEF), which is

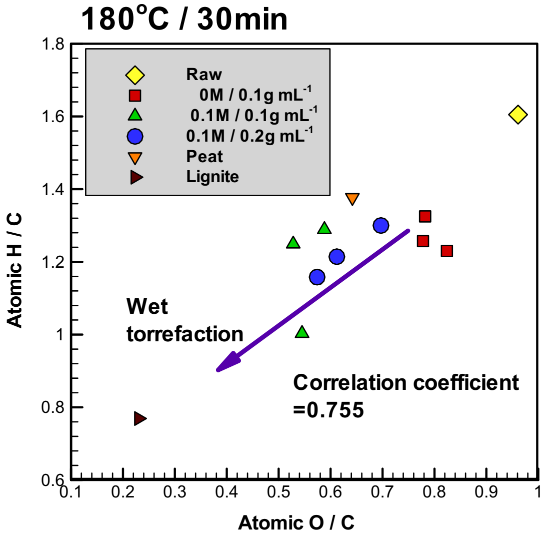

Fig. 3. van Krevelen diagram of raw and torrefied bagasses as well as peat and lignite.

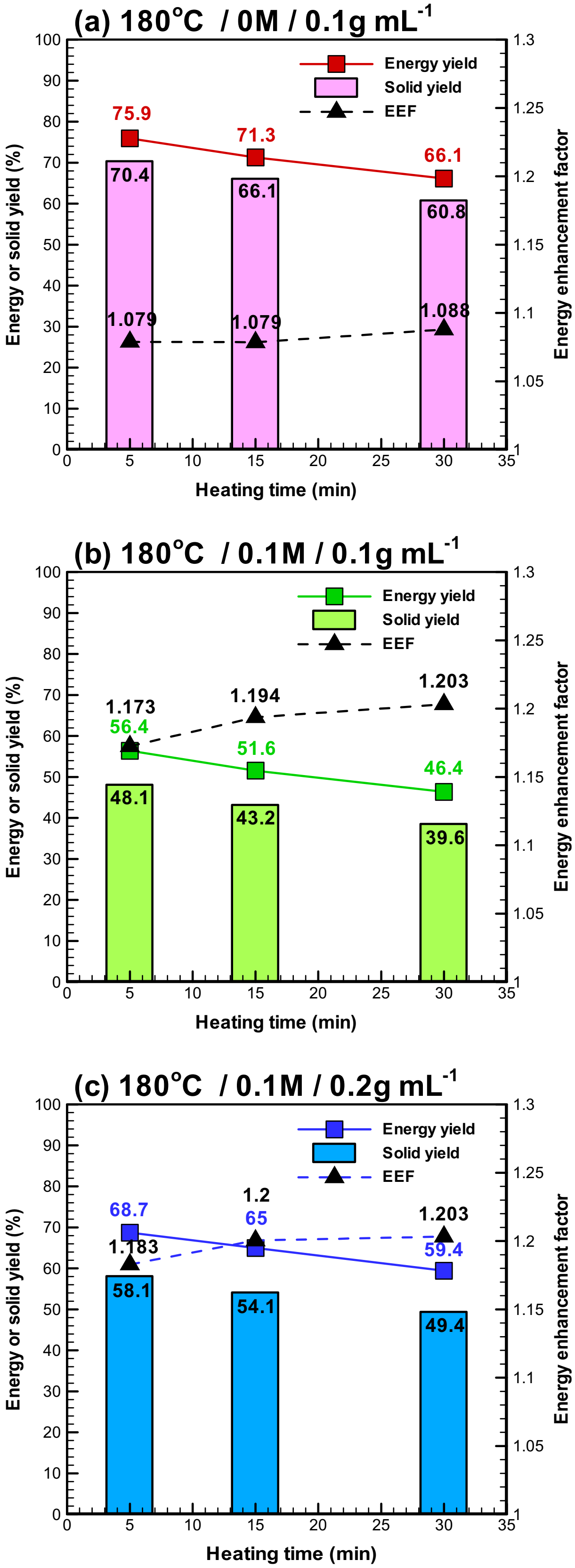

Fig. 4. Distributions of energy and solid yields as well as EEF at the operating conditions of (a) SLR = 0.1 g mL^{-1} with water torrefaction, (b) SLR = 0.1 g mL^{-1} with 0.1 M acid solution, and (c) SLR = 0.2 g mL^{-1} with 0.1 M acid solution.

Table 4
Comparison of HHV of raw bagasse and torrefied materials between measurement and prediction.

Equation	Correlation (HHV, MJ kg^{-1})
(1)	HHV = 0.3536FC + 0.1559VM − 0.0078Ash[a]
(2)	HHV = 0.3491C + 1.1783H + 0.1005S − 0.1034O − 0.0151N − 0.0211Ash[b]
(3)	HHV = 0.0893L[c] + 16.9742[d] (For wood biomass)
(4)	HHV = 0.0877L[c] + 16.4951[d] (For non-wood biomass)

[a] Parikh et al. (2005).
[b] Channiwala and Parikh (2002).
[c] Lignin (wt.%).
[d] Demirbas (2001).

defined as the ratio of higher heating value (HHV) of torrefied bagasse to the raw one, the HHV of bagasse with water torrefaction is amplified by a factor of around 8–9% (Fig. 4a). When bagasse is torrefied by acid solution, the solid yield is further lessened. Corresponding to SLR = 0.1 and 0.2 g mL^{-1} with 30 min heating, 39.6 and 49.4 wt.% of bagasse are retained (Fig. 4b and c). This behavior is consistent with the observation of Lu et al. (2011) where it was reported that increasing SLR caused the decrease in hydrolysis efficiency of biomass. The EEF can be lifted up to 1.203 (Fig. 4b and c), implying that the energy density of bagasse is enhanced over 20%. A comparison between the cases of SLR = 0.1 and 0.2 g mL^{-1} suggests that the latter is a better operation in that more solid can be retained from wet torrefaction with the same EEF, thereby giving a higher energy yield.

The HHV of biomass can be predicted in terms of proximate analysis (Parikh et al., 2005), elemental analysis (Channiwala and Parikh, 2002) or fiber analysis (Demirbas, 2001). The related correlations are tabulated in Table 4. To evaluate the feasibility of the correlations, the measured and predicted calorific values of torrefied bagasse are summarized in Table 5. The relative error between measurements and predictions are less than 15%. This illustrates that the established correlations for predicting the HHV of raw biomass are also applicable in estimating the HHV of biomass with wet torrefaction. The correlation in terms of fiber analysis of non-wood biomass, namely, Eq. (4), gives the best estimation. The correlation is thus recommended for predicting the calorific value of torrefied bagasse. This also reflects that lignin plays an important role in contributing the heating value of torrefied lignocelluloses.

3.6. Dry torrefaction

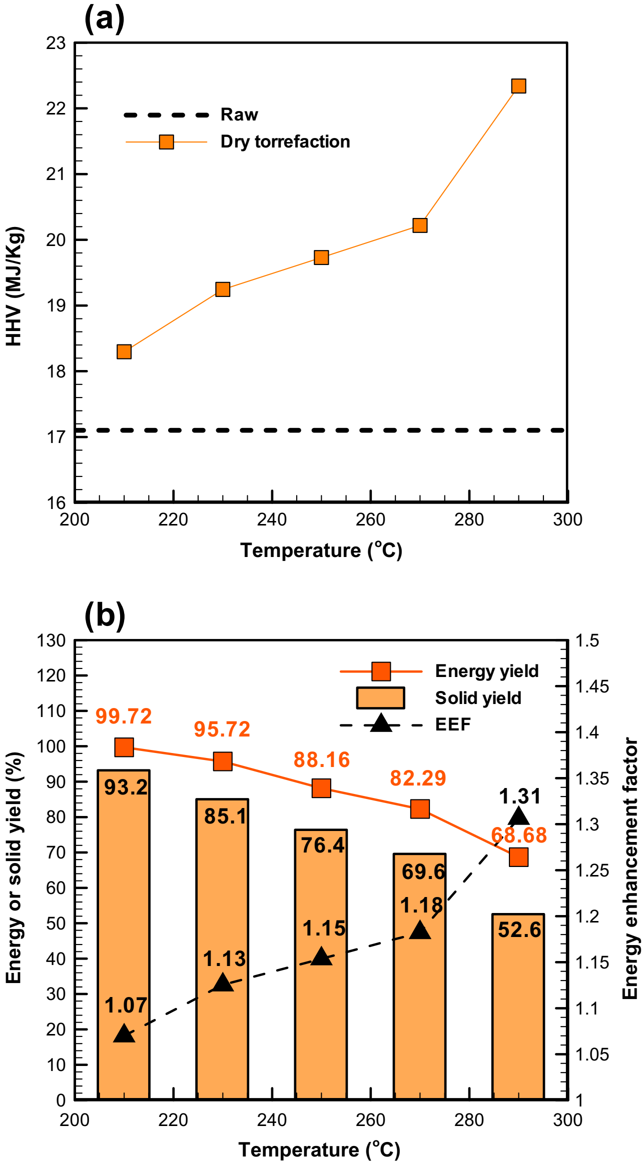

Fig. 5. Distributions of (a) higher heating value and (b) energy and solid yields as well as EEF of bagasse undergoing dry torrefaction.

In examining the HHV of bagasse experiencing dry torrefaction (Fig. 5a), the value rises from 17.1 (raw bagasse) to 22.3 MJ kg^{-1} (torrefied at 290 °C). Similar to wet torrefaction, the energy yield is always higher than the solid yield (Fig. 5b). Within the investi-

Table 5
Comparison of HHV of raw bagasse and torrefied materials between measurement and prediction.

Material	SLR[b] (g mL^{-1})	H_2SO_4 (M)	Heating time (min)	Measurement (MJ kg^{-1})	Prediction, Eq. (1) (MJ kg^{-1})	Prediction, Eq. (2) (MJ kg^{-1})	Prediction, Eq. (3) (MJ kg^{-1})	Prediction, Eq. (4) (MJ kg^{-1})
Raw bagasse				17.10	18.33	14.80	18.48	18.07
Pretreated materials	0.1	0	5	18.45	16.78	15.81	18.74	18.34
			15	18.45	16.89	16.58	19.14	18.76
			30	18.60	17.07	16.69	19.06	18.67
	0.1	0.1	5	20.05	18.06	19.86	19.91	19.56
			15	20.41	18.39	20.78	20.65	20.34
			30	20.58	19.18	19.22	21.21	20.92
	0.2	0.1	5	20.23	18.10	17.84	19.93	19.59
			15	20.53	18.38	19.61	20.23	19.90
			30	20.58	18.96	19.00	20.62	20.30
Relative error[a] (%)					−7.19 to 10.52	−1.78 to 14.33	−8.05 to 1.46	−5.65 to 3.17

[a] Relative error (%) $= \frac{HHV_{measurement} - HHV_{prediction}}{HHV_{measurement}} \times 100$
[b] SLR: solid-to-liquid ratio.

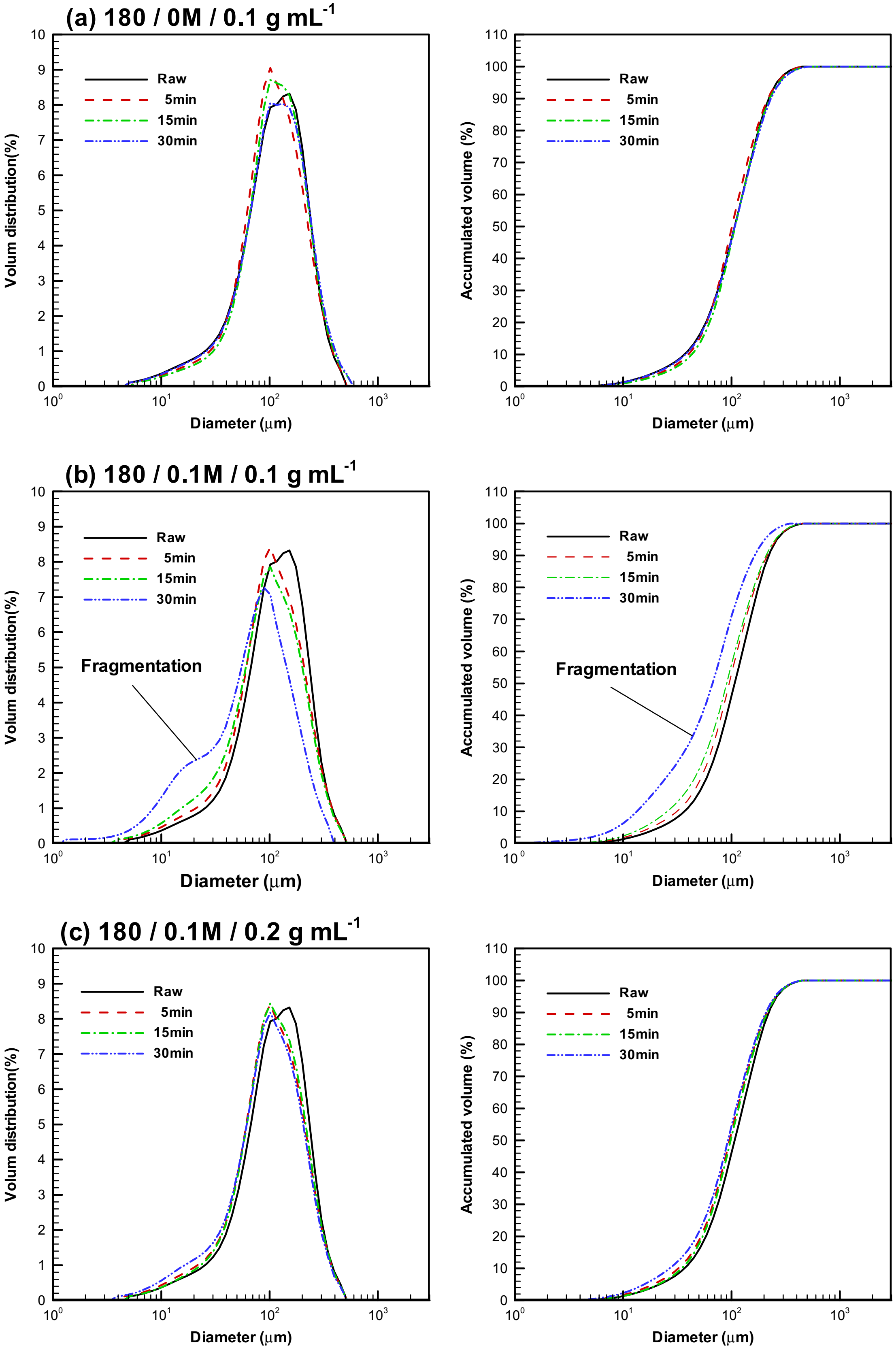

Fig. 6. Distributions of particle size and accumulated particle size of bagasse at the operating conditions of (a) SLR = 0.1 g mL^{-1} with water torrefaction, (b) SLR = 0.1 g mL^{-1} with 0.1 M acid solution, and (c) SLR = 0.2 g mL^{-1} with 0.1 M acid solution.

gated range of temperature (i.e. 210–290 °C), the EEF grows from 1.07 to 1.31. For wet torrefaction, 20% of energy density is enhanced if bagasse is torrefied in an acid solution with the heating time of 30 min. In dry torrefaction, the energy density is improved by 18% when bagasse is torrefied at 270 °C for 1 h. Accordingly, if 20% of EEF is achieved, the temperature of wet torrefaction (180 °C) is lower than that of dry torrefaction around 100 °C. However, it should be pointed out that the energy yield of bagasse at SLR = 0.2 g mL^{-1} with 30 min heating is lower than that of dry torrefactions at 270 °C around 10%.

3.7. Particle size distribution

The particle size distribution plays an important role in realizing the situation of solid particle reaction (Chen et al., 2007). From the profiles of bagasse particle size at various operating conditions, the impact of water torrefaction on particle size is relatively slight (Fig. 6a). Once bagasse is torrefied by the acid solution at SLR = 0.1 g mL^{-1}, the characteristic of particle fragmentation is apparently exhibited, especially for the case of 30 min heating time. The behavior of particle fragmentation is also observed at SLR = 0.2 g mL^{-1}; but it is not as significant as that at SLR = 0.1 g mL^{-1}, as a result of less acid solution utilized for torrefaction.

4. Conclusions

Wet torrefaction of sugarcane bagasse has been investigated and compared to dry torrefaction. Compared to using water, hydrothermal carbonation of bagasse can be enhanced greatly if the dilute sulfuric acid solution is employed along with 30 min heating time. When the energy density of bagasse is enhanced by 20%, the temperature of wet torrefaction can be lower than that of dry torrefaction around 100 °C. But the energy yield from wet torrefaction is less than that from dry torrefaction around 10%. It is also found that particle fragmentation becomes more pronounced when wet torrefaction is more severe.

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